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REVIEW

Green synthesis of nanoparticles using plant extracts: a review

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Abstract
Green synthesis of nanoparticles has many potential applications in environmental and biomedical fields. Green synthesis aims in particular at decreasing the usage of toxic chemicals. For instance, the use of biological materials such as plants is usually safe. Plants also contain reducing and capping agents. Here we present the principles of green chemistry, and we review plant-mediated synthesis of nanoparticles and their recent applications. Nanoparticles include gold, silver, copper, palladium, platinum, zinc oxide, and titanium dioxide.

Keywords Green synthesis · Nanoparticles · Sustainability · Waste treatment · Dye degradation

List of abbreviations

4-AP	4-Amino phenol
BET	Brunauer–Emmett–Teller
CR	Congo red
DLS	Dynamic light scattering
2,4-DNPH	2,4-Dinitrophenilhydrazine
EDS	Energy-dispersive spectroscopy
FESEM	Field emission scanning electron microscopy
FTIR	Fourier transform infrared
GO	Graphene oxide
MB	Methylene blue
MO	Methyl orange
MR	Methyl red
4-NP	4-Nitrophenol
RhB	Rhodamine B
RGO	Reduced graphene oxide
SERS	Surface-enhanced Raman scattering
TWW	Tannery wastewater

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Introduction

"Nanotechnology deals with the processing of separation, consolidation, and deformation of materials by one atom or by one molecule" was well defined by Professor Norio Taniguchi, Tokyo Science University, for the term "nanotechnology." In his words, it deals with the branch of the science of manipulating matter on an atomic or molecular scale. Nanotechnology evolved as the scientific innovation in the twenty-first century. It is an interdisciplinary area that comprises the invention, handling, and use of those materials scaling in size less than 100 nm. It deals to govern matter at the molecular level and has firmly entered the realm of the vast area of applications (Mansoori 2005). In nanotechnology, day-by-day incredible growth has unbolted up innovative applied and fundamental frontiers in a new branch of research, i.e., materials science and engineering, such as surface-enhanced Raman scattering (SERS), nanobiotechnology, quantum dots, and applied microbiology (Dvir et al. 2011). Nanotechnology is playing a critical role in many significant technologies via nanoscale structures (nanoparticles) in areas of optics, electronics, biomedical science, mechanics, drug-gene delivery, chemical industry, optoelectronic devices, nonlinear optical devices, catalysis, space industries, energy science, and photoelectrochemical applications (Singh et al. 2019). Nanoparticles are the area of excessive interest because of their large surface to volume ratio and tremendously small size (in nm) which leads to both physical and chemical modifications in their properties in comparison with the majority of the same chemical composition (Ray 2010; Bakand et al. 2012).

Many researchers and scientists have shown great interest in their unique features and found that, however, these have outstanding applications in various fields, but numerous nanoparticle materials revealed toxicity at the nanoscale size. To overcome the problem of toxicity, nanotechnology and green chemistry merge to fabricate nature-friendly nanoparticles via plants, microbes, etc. (Lateef et al. 2016). Researchers have developed many synthetic routes for nanoparticle fabrication which unveiled a notable benefit to nature & environment via clean, nontoxic, and environmentally adequate "green chemistry" methods which include organisms such as bacteria, fungi, plants (Duan et al. 2015). Numerous studies have been already done for the synthesis of metal nanoparticles using bacteria like *Bacillus subtilis* (Sundaram et al. 2012) and using some bacteria such as *Penicillium sp.* (Du et al. 2011), *Fusarium oxysporum* (Nelson et al. 2005). Using plant extracts for the synthesis of numerous nanoparticles is the theme of this review as it is the most implemented method of eco-friendly and green approach toward chemistry. This route attracted the attention of researchers and scientists due to easy availability and wide distribution of plants as well as it is safe to use and source of various metabolites.

Principle of sustainable and green chemistry

"Green Chemistry" for "Sustainable development" has been universally studied for less than 15 years (Clark and Macquarrie 2008). Sustainable development can be defined as the development which encounters the needs of the present with balancing the capability of future generations to meet their individual needs (Robert et al. 2005). Sustainable development has specific significance for chemistry-based industries due to its concern with evidence of pollution and the rough use of natural resources (Omer 2008). Chemistry has extended been supposed as a hazardous science, and frequently, the public associates the word chemical with hazard and toxic (Wilson and Schwarzman 2009). Generally, there are many ways to diminish risk by using protection called protective gear, but when safety precaution fails, the risk of hazards and exposure increases. In the condition of high hazards and failing of exposure, the consequences can be disastrous which means it causes injury or death (Crowl and Louvar 2001; Anastas and Eghbali 2010). Therefore, designing harmless sustainable chemicals and procedures needs striving to decrease the intrinsic hazards to the least and limiting the danger of accident and damage (Centi and Perathoner 2009; Al Ansari 2012).

Green synthesis of nanoparticles

The three foremost conditions for the synthesis of nanoparticles are the selection of green or environment-friendly solvent, a good reducing agent, and a harmless material for stabilization. For the synthesis of nanoparticles, extensive synthetic routes have been applied in which physical, chemical, and biosynthetic routes are very common. Generally, the chemical methods used are too expensive and incorporate the uses of hazardous and toxic chemicals answerable for various risks to the environment (Nath and Banerjee 2013). The biosynthetic route is a safe, biocompatible, environment-friendly green approach to synthesize nanoparticles using plants and microorganisms for biomedical applications (Razavi et al. 2015). This synthesis can be carried out with fungi, algae, bacteria, and plants, etc. Some parts of plants such as leaves, fruits, roots, stem, seeds have been used for the synthesis of various nanoparticles due to the presence of phytochemicals in its extract which acts like stabilization and reducing agent (Narayanan and Sakthivel 2011). For nanoparticle synthesis, numerous biological and physicochemical pathways fall under two discrete classes: a bottom-up and top-down approach, Fig. 1. Nanoparticles synthesis via various biological and physicochemical approaches is shown in Fig. 1.

Bottom-up approach

The bottom-up approach involves the generation of nanoparticles from small units like molecules and atoms or through the self-assembly of atoms into new nuclei, which further grow into a particle possessing nanoscopic dimensions and employing various chemical and biological methods, Fig. 2a.

Top-down approach

In this approach, nanoparticles are formed by size reduction method that means suitable bulk material reduces to small units with the use of appropriate lithographic methods, for example crushing, spitting, and milling, Fig. 2b.

The stability, shape, and size of nanoparticles can be precise by controlling the temperature, pH, concentration of plant extract, and metal salt solution as well as incubation time. *Siddiqi* et al. (Siddiqi and Husen 2016) reviewed the synthesis of palladium and platinum nanoparticles and presented a complete process of synthesis of nanoparticles as well as their potential application as diagnostic, biosensors, medicine, catalyst, and pharmaceuticals, Fig. 3.

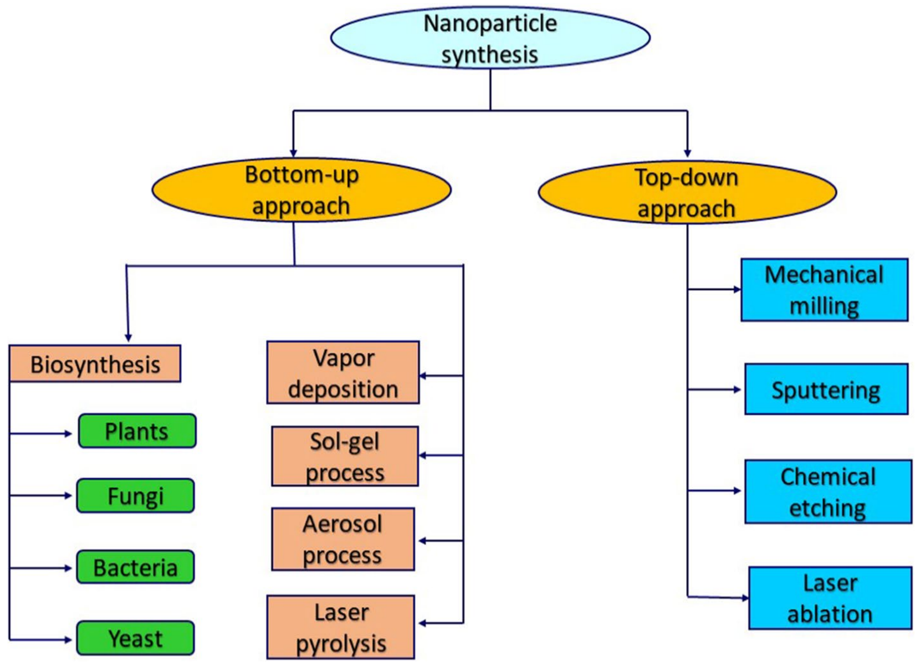

Fig. 1 Nanoparticles synthesis via biological and physicochemical approaches

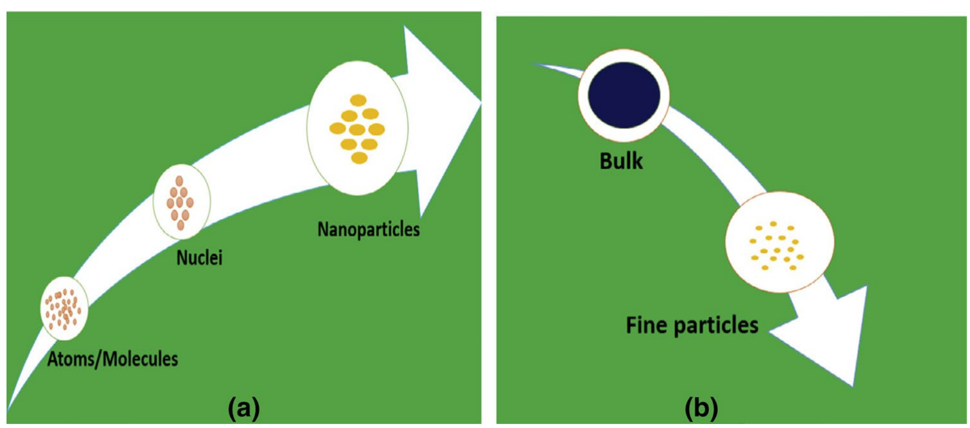

Fig. 2 Protocols for nanoparticle synthesis: **a** bottom-up approach for the synthesis of nanoparticles via self-assembling of various nuclei and **b** top-down approach for the synthesis of nanoparticles via size reduction (reprinted from Ahmed et al. 2016a with permission from Elsevier)

Role of plants in green synthesis of nanoparticles

In the biosynthesis of nanoparticles environmentally accepted "green chemistry" concept has been applied for the development of clean and environment-friendly nanoparticles which involves bacteria, fungi, plants, actinomycetes, etc., which is said to be "green synthesis" (Pal et al. 2019). Biosynthesis of nanoparticles by using the above organisms epitomizes a green substitute for the invention of nanoparticles with innovative properties. In these syntheses, unicellular and multicellular organisms are allowed to react (Mohanpuria et al. 2008).

Plants are known as chemical factories of nature which are cost-efficient and need little maintenance. Plants have revealed outstanding potential in heavy metal detoxification as well as accumulation by which environmental pollutants problem can be overcome because very small traces of these heavy metals are also toxic even at very low concentrations (Shahid et al. 2017). There are advantages for nanoparticle synthesis with plant extract as compared to some other biological synthesis such as by microorganisms as they can be done by complex actions of preserving microbial cultures (Hulkoti and Taranath 2014). One advantage of plant-assisted nanoparticle synthesis is the kinetics for this route is ample higher than in other biosynthetic approaches equivalent to chemical nanoparticle preparation. Various parts of plants such as fruit, leaf, stem, root have been widely used for green synthesis of nanoparticles due to the excellent phytochemicals they produce (Iravani 2011). For nanoparticle synthesis, the part of the plant which has to be used in synthesis can be washed and boiled with distilled water. After squeezing,

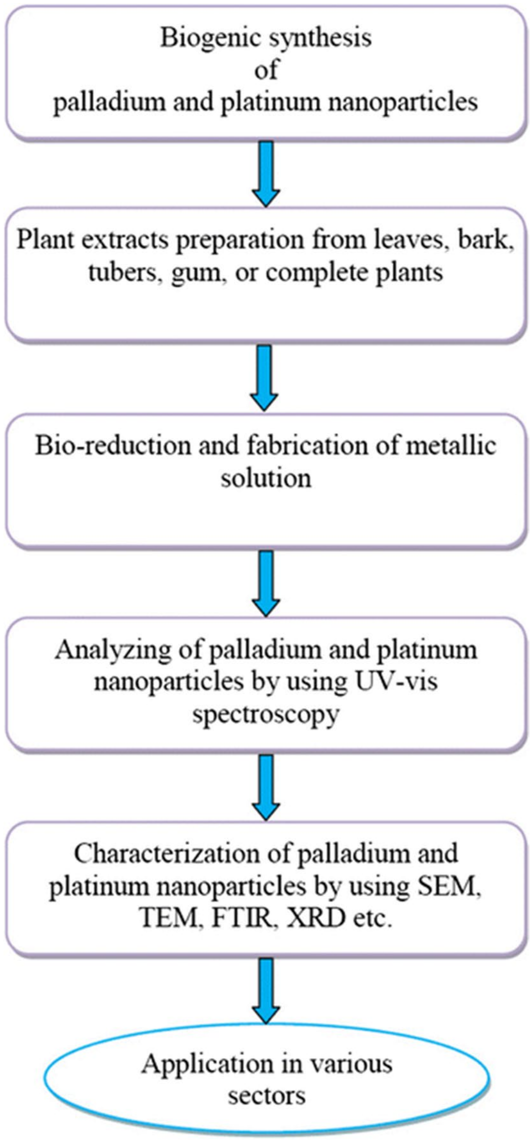

Fig. 3 Flowchart for synthetic route, characterization and applications of green synthesis of palladium and platinum nanoparticles from plant's extract. Reprinted from Siddiqi and Husen (2016) with permission from Springer

filtering, and adding respective solutions which nanoparticles we want to synthesize, solution color starts changing unveiled the formation of nanoparticles and we can separate these, Fig. 4. Synthesis via natural plant extract is an environment-friendly and cheap process by which we can avoid any utilization of intermediate base groups. Literature suggested accumulation, detoxification, and phytoremediation of toxic metals by some plants, such as *Thlaspi caerulescens, Maytenus founieri, Arabidopsis helleri, Sesbania drummondii, Acanthopanax sciadophylloides, Clethra barbinervis, and Brassica juncea*. The use of these plants in heavy metal elimination from aqueous solutions has gained considerable attention due to its great potential for the removal of pollutants and toxicity from wastes in an eco-friendly method (Carolin et al. 2017). Many nanoparticles such as gold, silver, zinc oxide, iron have been synthesized very easily by adopting a green approach (Singh et al. 2018). The phytocompounds present in the plant extract such as polyols, terpenoids, polyphenols are responsible for metallic ions bioreduction (Ovais et al. 2018).

Extraction of biologically produced metal nanoparticles

Nanoparticles can be synthesized by flowers and leaves of plants where parts of plants are thoroughly washed with the help of tap water and sterilized by double-distilled water followed by drying at room temperature. The dried sample goes to the process of weighing and crushing. Afterward, plants extract is mixed with Milli-Q H_2O as per desired concentration and boiled with continuous stirring. The obtained solution is then filtered with Whatman filter paper, and the part in which there is a clear solution was useful for sample (plant extract) (Wang et al. 2019).

Types of nanoparticles

A wide variety of nanoparticles are synthesized by green approach up to now and characterized by ultraviolet–visible spectroscopy, Fourier transform infrared spectroscopy (FTIR), Raman spectroscopy, photoluminescence analysis (PL), transmission electron microscopy (TEM), scanning electron microscopy (SEM), energy dispersion analysis of X-ray (EDAX), X-ray diffractometer (XRD), atomic force microscopy (AFM), field emission scanning electron microscopy (FE-SEM), thermal-gravimetric differential thermal analysis (TG-DTA), X-ray photoelectron microscopy (XPS), attenuated total reflection (ATR), dynamic light scattering (DLS) and UV–visible diffuse reflectance spectroscopy (UV-DRS).

Ag nanoparticles

For the green synthesis of silver nanoparticles, the key requirements are silver metal ion solution and a reducing biological agent. The easiest and inexpensive method for silver nanoparticles production is silver ion's reduction and stabilization by a fusion of biomolecules such as polysaccharides, vitamins, amino acids, proteins, saponins, alkaloids, terpenes, and phenolics (Tolaymat et al. 2010). Silver nanoparticles can be extracted from many medicinal plants such as *Saccharum officinarum* (Chaudhari et al. 2012),

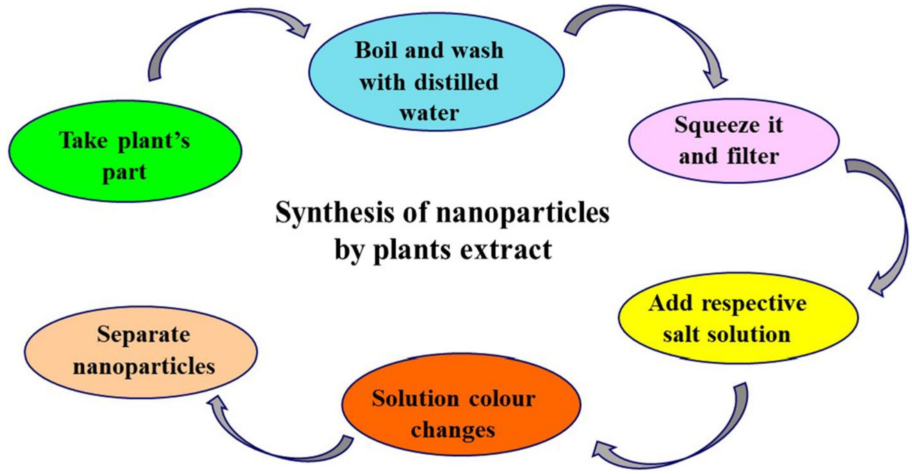

Fig. 4 Environment-friendly and cheap route for the green synthesis of nanoparticles using plants extract

Helianthus annus (Dubchak et al. 2010), *Cinamomum camphora* (Huang et al. 2008), *Oryza sativa* (Dar et al. 2016), *Aloe vera* (Chandran et al. 2006b), *Capsicum annuum* (Li et al. 2007), *Medicago sativa* (Lukman et al. 2011), *Zea mays* (Rajkumar et al. 2019), *Magnolia Kobus* (Lee et al. 2014) in the biological and pharmaceutical field.

For the synthesis of shape-controlled and stable silver nanoparticles, ecofriendly bio-organisms found in the extract of plants comprise protein treats as a capping agent and reducing agent. Modification of silver nanoparticles by polymers and surfactants revealed high microbial activity against Gram-negative and Gram-positive bacteria (Sharma et al. 2009). Some researchers have done the synthesis of silver nanoparticles by methanolic extract of *Eucalyptus hybrida* plant (Dubey et al. 2009). Silver nanoparticles can be obtained by boiling 10 g leaves of *Nelumbo lucifera* in 100 ml distilled water. The filtrate solution (12 ml) was further treated with 1 mM aqueous solution of $AgNO_3$ (88 ml) and incubated in dark at room temperature. A brownish yellow color solution was designated as the formation of silver nanoparticles (AgNPs) (Santhoshkumar et al. 2011). Leaf extract of *Hibiscus rosa sinensis* was added to the 10^{-3} M solution of $AgNO_3$ (25 ml) and stirred for 5 min dynamically. At 300 K temperature reduction took place and completed in 30 min with the light brown silver nanoparticles (Philip 2010). Silver nanoparticles were also synthesized by adding seed extract (5 ml) of *Jatropha curcas* to 10^{-3} M aqueous solution of $AgNO_3$ (20 ml) and heating the mixture at 80 °C for 15 min. Meanwhile, the solution became reddish indicated the synthesis of silver nanoparticles (Bar et al. 2009).

Kumar and labmates represented biosynthesis of silver nanoparticles from silver precursors by bark extract of *Cinnamon zeylanicum* plant. They suggested that the use of plant materials is considered green technology without using any harmful chemicals. Reduction of silver ions and alteration of these to nanosized silver particles are mainly due to water-soluble organics present in such plant materials. Some other factors also played a unique role in the biosynthesis of silver nanoparticles such as pH of medium controlled the size of nanoparticles. The bark extract of *Cinnamon zeylanicum* plant formed more silver nanoparticles as compared in powder form. This indicated great obtainability of reducing agents in bark extract. The charge on the surface was found highly negative by zeta potential studies, and EC50 values were found 11 ± 1.72 mg/L against *Escherichia coli* BL-21 strain. Hence, the bark extract of the above-discussed plant is the perfect source of silver nanoparticles synthesis with high antimicrobial activity (Sathishkumar et al. 2009).

Au nanoparticles

Gold nanoparticles have attracted considerable attention among all metallic nanoparticles due to their uniqueness in a high potential for use in medicine and biology field (Jain et al. 2006), more biocompatible nature (Sperling et al. 2008), tunable surface plasmon resonance (Huang and El-Sayed 2010), low toxicity (Jeong et al. 2011), strong scattering and absorption (El-Sayed et al. 2005), facile synthesis methods, easy surface functionalization (Ghosh et al. 2008), etc. In the mechanism of synthesis of gold nanoparticles, various chemical moieties in biogenic complexes treat as reducing agents and react with gold metal ion with the result of its reduction and preparation of nanoparticles, Fig. 5. Some studies revealed that in plants extract, some biomolecules like flavonoids, phenols, protein, etc., act significantly in the reduction of metal ions and the topping of gold nanoparticles (Fig. 6).

For gold nanoparticles synthesis, the first study was performed in 2003 by Shankar and his group by using the geranium leaf extract for reducing and capping agent. This reaction was carried out for 48 h by using the terpenoids present in leaf extract which was responsible for the reduction of gold ions to gold nanoparticles. Morphological studies

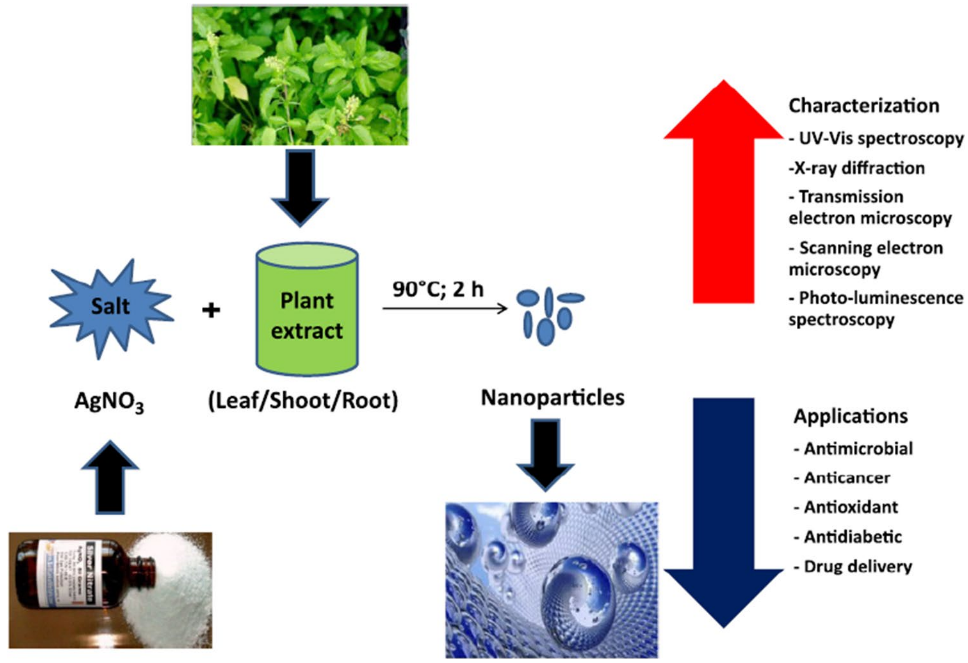

Fig. 5 Green synthesis of silver nanoparticles by plants extract and $AgNO_3$, its characterization and applicants in various biomedical fields. Reprinted from Pal et al. (2019) with permission from Elsevier

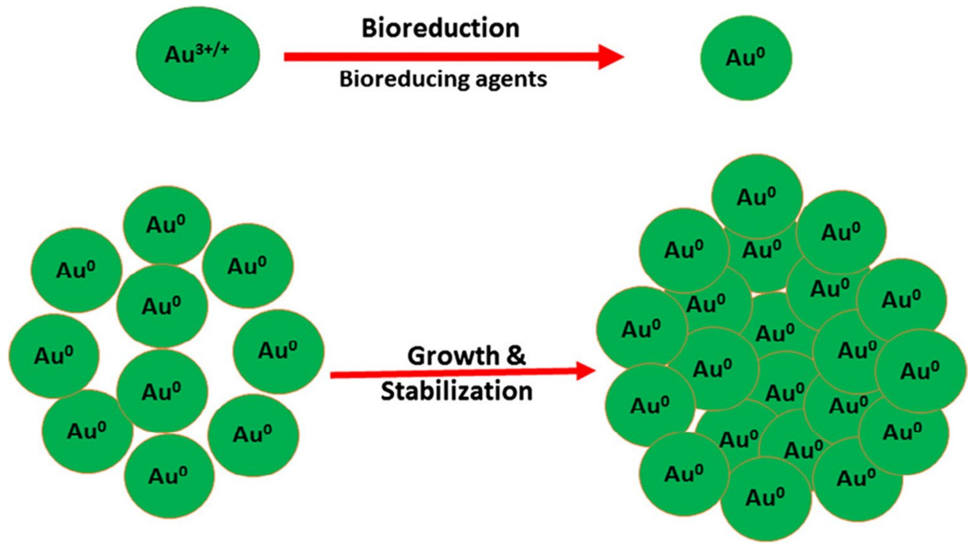

Fig. 6 Synthetic route of gold nanoparticles by bioreduction and stabilization of chemical moieties present in the biogenic complexes. Reprinted from Ahmed et al. (2016b) with permission from Elsevier

suggested that these nanoparticles were formed in numerous shapes such as triangular, spherical, decahedral, and icosahedral (Shankar et al. 2003). Further, they synthesized gold nanoparticles with leaf extract of *Azadirachta indica* in 2.5 h reaction time. The neem extract having an abundance of terpenoids and flavanones was probably absorbed on the surface of the nanoparticles and controlled their stability for 4 weeks. Morphological studies revealed the shape of nanoparticles was spherical and chiefly planar in which majority was of triangular, while some were hexagonal (Shankar et al. 2004).

For tuning the shape and size of gold nanoparticles, *Aloe vera* leaf extract was used by Chandran et al. (2006a). The shape and size were seemed dependent on the quantity of leaf extract used and found triangle and 50–350 nm, respectively. Triangles of nanogold in larger sizes were formed by using less amount of leaf extract to $HAuCl_4$ solution, while enhancing the quantity of leaf extract spherical nanoparticles were also formed in more quantity resulting in the decrement in the ratio of nanotriangle to nanospherical particles. By using low extract quantity of mushroom extract, some anisotropic gold nanoparticles were achieved having maxima of triangles and prisms, while very a smaller number of hexagons and spheres were achieved. When the quantity of mushroom extract was increased, hexagons and spheres were increased in the morphology of nanoparticles and the size of nanoparticle was much smaller, while there was a decrement in nanotriangles. When the extracted quantity was increased to its highest concentration, the nanoparticles formed were in 25 nm size. The nanoparticles were also affected by temperature which was cleared by receiving hexagons at 313 K temperature at the highest extract quantity, while nanoparticles in dendrites shapes were achieved at 353 K temperature (Philip 2009).

Temperature effect was also seen by Song et al. (Song et al. 2009) in the biosynthesis of gold nanoparticles by *Diopyros kaki* and *Magnolia kobus* leaf extracts. They suggested that at higher extract concentration and higher temperature, nanoparticles produced were smaller in size, and the shape of these was found spherical, while at lower extract concentration and temperature, larger nanoparticles having various morphologies were obtained. Leaf extract of *Terminalia catappa* was used as a reducing and capping agent for the synthesis of gold nanoparticles. Hasty reduction of chloroaurate ions to gold nanoparticles was performed by treating chloroauric acid solutions with leaf extract. Morphological studies by transmission electron microscopy analysis suggested the nanoparticles were formed in the range of 10–35 nm (Ankamwar 2010). Morphological studies of gold nanoparticles synthesized by coriander leaf extract were analyzed by high-resolution transmission electron microscopy and revealed triangle, truncated triangles, spherical and decahedral shapes, and size of 6.75–57.91 nm having a usual size of 20.65 nm, Fig. 7. These nanoparticles were found stable in solution at room temperature for 1 month (Narayanan and Sakthivel 2008).

Zhang and labmates used chloroplast of *Trifolium* leaves which were collected from the campus of Shanghai Jiao Tong University, China. They used chloroplast of leaves as a reductant and stabilizer. These nanoparticles showed high crystallinity having plane (111) as predominant orientation and spherical particles of size 20 nm in diameter. Toxicology assays against gastric mucous cell line GES-1 and gastric cancer cell line MGC-803 by using 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide (MTT) method revealed the nontoxic nature of nanoparticles. SERS (surface-enhanced Raman spectroscopy) studies revealed the capability of gold nanoparticles could substantially enhance the Raman signals of rhodamine 6G without any treatment. Hence, these nanoparticles were biocompatible as well as having immense potential for hypersensitive detection of the biomarker in vivo and in vitro studies (Zhang et al. 2011). Recently, Islam and his coworkers synthesized gold nanoparticles with leaves extract of *Salix alba*.

Scanning electron microscopy and atomic force microscopy studies revealed that the size of nanoparticles was 50–80 nm and 63 nm, respectively. The involvement of amine, amide, and aromatic groups in successful reduction and capping for gold nanoparticles was confirmed by FTIR studies. These nanoparticles were highly stable in various pH solutions as well as various volumes of salts but found unstable at eminent temperature. Gold nanoparticles synthesized by leaf extract of *Salix alba* were suitable for numerous pharmaceutical and biomedical applications due to its superior antifungal activity, excellent antinociceptive, and muscle relaxant properties (Islam et al. 2019). Gold nanoparticles were also synthesized recently by various plant extracts such as *Coffea Arabica* (Keijok et al. 2019), *Croton Caudatus Geisel* leaf extract (Kumar et al. 2019), *Bacillus marisflavi* (Nadaf and Kanase 2019), *Croton sparsiflorus* leaves extract (Boomi et al. 2020), the leaf extract of *Citrus limonum* (Bhagat et al. 2020), *Aeromonas hydrophila* (Fernando and Judan Cruz 2020).

Pd and Pt nanoparticles

Palladium and platinum both are silvery-white expensive metals having high density. Biosynthesis of both nanoparticles from plants has attracted wide attention of many researchers due to eco-friendly, sustainable, and economical

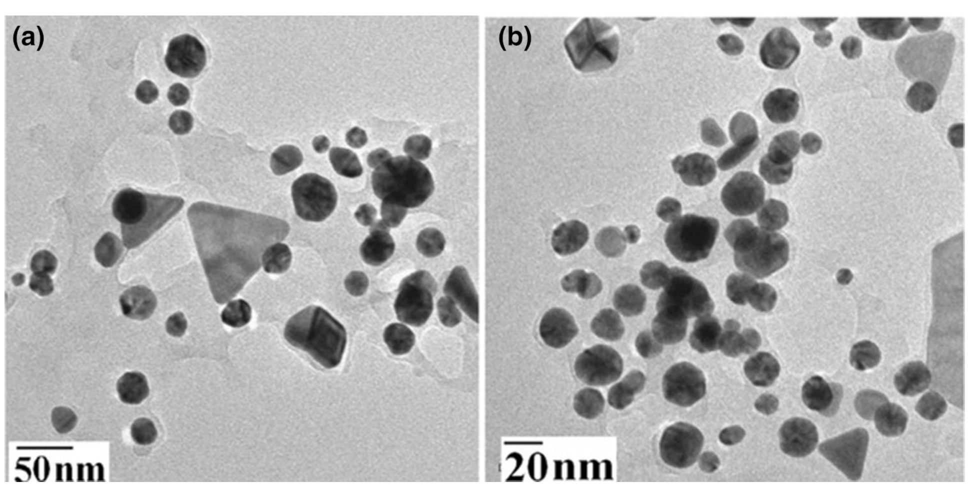

Fig. 7 Transmission electron microscopy (TEM) of gold nanoparticles synthesized by leaf extract of coriander. Reprinted from Narayanan and Sakthivel (2008) with permission from Elsevier

nature. Green synthesis of Pd and Pt nanoparticles has been reported using various plant extracts such as *Cinnamomum camphora*, *Gardenia jasminoides*, *Pinus resinosa*, *Anogeissus latifolia*, *Glycine max*, *Ocimun sanctum*, *Curcuma longa*, *Musa paradisica*, *Cinnamom zeylanicum*, *Pulicaria glutinosa*, *Doipyros kaki*, and many more (Siddiqi and Husen 2016).

When a methanolic extract of *Catharanthus roseus,* which is a mixture of eight compounds comprising –OH groups and responsible to reduce the metal ion to metal nanoparticles, was stirred for 1 h with an aqueous solution of $[Pd(OAc)_2]$ at 60 °C, solution color was changed revealed the formation of Pd nanoparticles which showed the absorption peak at 360–400 nm range and morphological studies also supported the formation of spherical nanoparticles of 40 nm size, Fig. 8 (Kalaiselvi et al. 2015).

Palladium nanoparticles were also fabricated using protein-rich soybean leaf extract containing amino acids. Confirmation of nanoparticles formation was done by ultraviolet–visible, Fourier transform infrared spectroscopy, and morphology was confirmed by transmission electron microscopy revealing 15-nm size nanoparticles. Spherical particles of 5 nm size were derived by leaf extract of *Anacardium occidentale* (Sheny et al. 2012). Renewable and nontoxic black tea leaves (*Camellia sinensis*) extract were also used as reducing and stabilizing agent in Pd nanoparticles preparation (Lebaschi et al. 2017). These nanoparticles were applicable in the reduction of 4-nitrophenol as well as in heterogeneous & effective catalysts in the Suzuki coupling reaction along with phenylboronic acid and aryl halides. The recycling capability of the catalyst was found 7 times without losing its catalytic activity, Fig. 9 (Lebaschi et al. 2017).

By using the extract of *Anogeissus latifolia* and palladium chloride, palladium nanoparticles were developed via the green route which was confirmed by intense brown color appearance and broad absorption spectrum in the ultraviolet–visible region. The average particle size of these was 4.8 ± 1.6 nm and spherical (Kora and Rastogi 2018). *Arsiya* et al. (Arsiya et al. 2017) fabricated 5–20-nm average-sized Pd nanoparticles by extract of *Chlorella vulgaris* in only 10-min duration. Fourier transform infrared spectroscopy (FTIR) studies suggested the involvement of polyol and amide group of *Chlorella vulgaris* in the reduction of metal ions to the nanoparticle.

Leaf extract of *Azadirachta indica* (neem) was used to reduce the Pt^{4+} ion into platinum nanoparticles of average size 5–50 nm. To reduce the chloroplatinic ions into platinum nanoparticles, the protein was found responsible (Ahmed et al. 2016c). The same synthesis was also done by tulsi leaf broth (*Ocimum sanctum*) with a reaction temperature of 100 °C and achieved irregularly shaped aggregates of about 23 nm size. The terpenoids, amino acids, ascorbic acid, certain proteins, and gallic acid present in tulsi leaf extract played an important role in the reduction of platinum ions. These nanoparticles opened up doors for water electrolysis applications (Soundarrajan et al. 2012). Some platinum nanoparticles were fabricated by Saudi's dates extract (Barni and Ajwa) as these are a rich source of antioxidants and have brilliant antibacterial and antifungal properties as well as these are excellent for therapeutic purposes, Fig. 10 (Al-Radadi 2019). Similarly, many researchers synthesized platinum nanoparticles by using plant extracts such as *Diopyros kaki* leaf extract (Song et al. 2010), *Prunus* × *yedoensis* tree gum extract (Velmurugan et al. 2016), *Terminalia chebula* (Kumar et al. 2013).

Cu nanoparticles

Copper nanoparticles are synthesized by various plant extracts such as *Aloe vera* flower extract via the reduction of aqueous copper ions. The formation of an average size of 40 nm Cu nanoparticles was confirmed by 578-nm peak at UV–Visible spectrometer (Karimi and Mohsenzadeh 2015).

Green synthesis of $Cu/GO/MnO_2$ nanocomposite was performed by leaf extract of *Cuscuta reflexa* leaf extract which is a rich source of numerous antioxidant phytochemicals such as Myricetin, Myricetin glucoside, Kaempferol-3-Oglucoside (Astragalin), Kaempferol-3-O-galactoside, Kaempferol, Quercetin, Quercetin-3-O-glucoside, Quercetin 3-O-galactoside, Oleic acid, Palmitic acid, Linoleic acid, Linolenic acid, Stearic acid, Isorhamnetol, Cuscutin, Cuscutalin, Azaleatin, Amarbelin, Dulcitol, Bergenine, Beta-sitosterol, Luteolin, Maragenin, and Coumarin. The above constituents are responsible for the conversion of

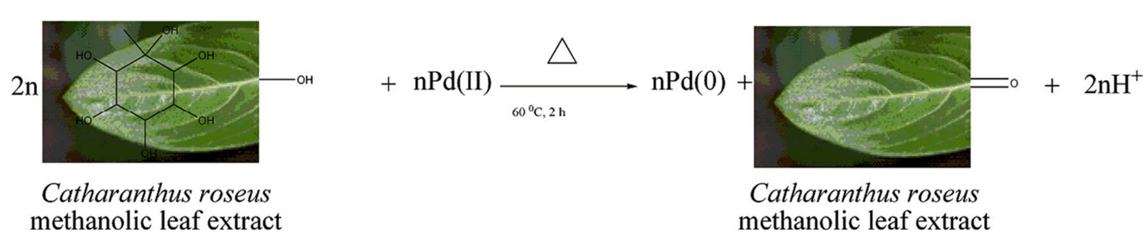

Fig. 8 Synthesis of palladium nanoparticles using *Catharanthus roseus* methanolic leaf extract and palladium ion. Reprinted from Kalaiselvi et al. (2015) with permission from Elsevier

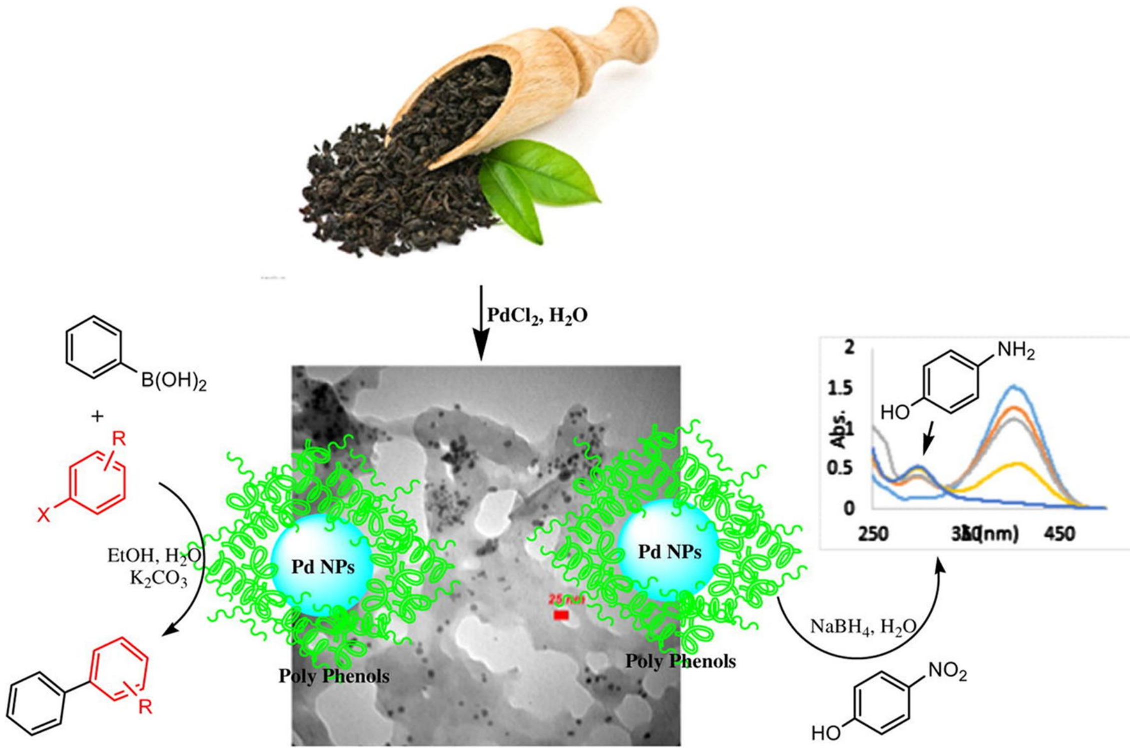

Fig. 9 Synthesis of Pd nanoparticles by black tea leaves (*Camellia sinensis*) extract, its catalytic activity in Suzuki coupling reaction, and reduction of 4-nitrophenol. Reprinted from Lebaschi et al. (2017) with permission from Elsevier

plant extract to a rich source of antioxidants for nanoparticle synthesis (Rahmatullah et al. 2010; Vijikumar et al. 2011; Naghdi et al. 2018).

The Cu nanoparticles were immobilized on graphene oxide/MnO_2 nanocomposites surface via the reduction of Cu^{+2} ions to Cu nanoparticles by using *Cuscuta reflexa* leaf extract, Fig. 11. These nanocomposites with Cu nanoparticles were used as the heterogeneous and recoverable catalyst for the reduction of rhodamine B, congo red, methylene blue, methyl orange, 4-nitro phenol, and 2,4-DNPH by $NaBH_4$ in an aqueous medium (Naghdi et al. 2018). Cheirmadurai and labmates prepared copper nanoparticles on a large scale by using henna leaves extract as a reductant. They prepared nanobiocomposites conducting film by these Cu nanoparticles and collagen fibers which were left away from leather industries. The film was suitable for numerous electronic device applications (Cheirmadurai et al. 2014). Large-scale synthesis of 20-50-nm-sized Cu nanoparticles was also done by using tamarind and lemon juice (Sastry et al. 2013). In situ synthesis of Cu nanoparticles on reduced graphene oxide/Fe_3O_4 was performed by using barberry fruit extract as a stabilizing and reducing agent and found useful in the active catalyst for the reaction of phenol with aryl halides to get *O*-arylation of phenol under the ligand-free condition as well as it was recoverable and used for multiple times without losing any catalytic activity (Nasrollahzadeh et al. 2015a).

ZnO nanoparticles

Zinc oxide nanoparticles have drawn considerable attention from researchers and scientists in the past 4–5 years due to its wide applications field of the biomedical field as well as in optics and electronics. ZnO nanoparticles are of great interest due to inexpensive to synthesize, safe, and easy method of synthesis. These nanoparticles possess high exciton binding energy of 60 meV and a large bandgap of 3.37 eV, and due to this, these show various semiconducting properties such as high catalytic activity, wound healing, antiinflammatory, ultraviolet filtering properties and extensively used in various cosmetics such as sunscreen. These nanoparticles revealed various biomedical applications too such as antifungal, antibacterial, drug delivery, antidiabetic, anticancer. Up to now, numerous works have been reported for ZnO synthesis and utilization by plants, microorganisms, and others. Plant parts like flower, root, seed, leaves, etc., are used for the synthesis of ZnO nanoparticles, Fig. 12.

ZnO nanoparticles can be synthesized by mixing of plant extract clear solution with 0.5 Mm solution of hydrated zinc sulfate/zinc oxide/zinc nitrate and boiling the above mixture at desired time and temperature to get effective mixing.

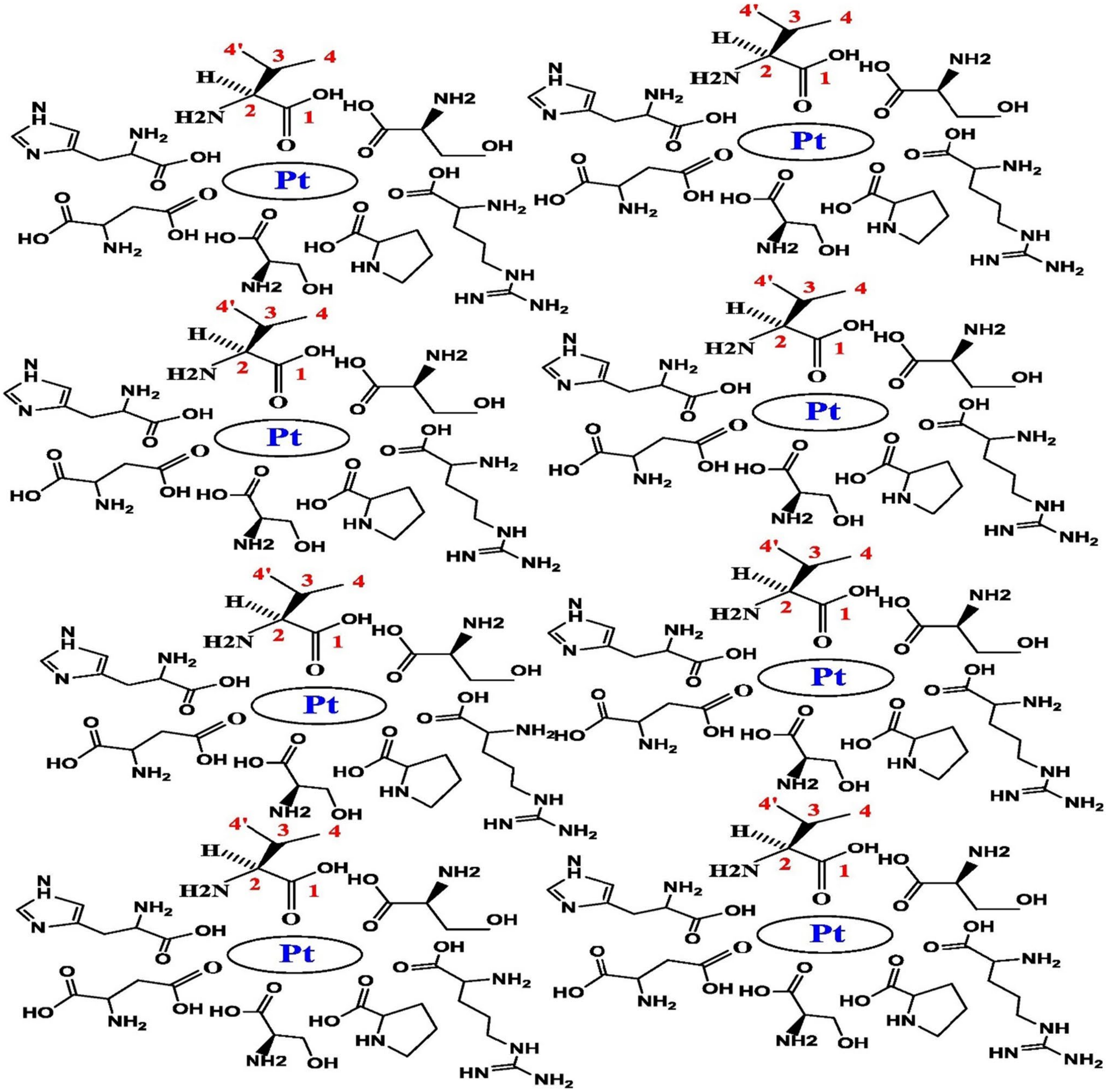

Fig. 10 Structure of platinum nanoparticles fabricated with antioxidant-rich source Saudi's Barni and Ajwa date extract. Reprinted from Al-Radadi (2019) with permission from Elsevier

Time, temperature, pH, and some other parameters can be optimized at this point. The reaction showed the change in color revealed confirmation of ZnO nanoparticles. These nanoparticles were characterized by various techniques for spectral, morphological, and thermal analysis. Energy-dispersive X-ray analysis (EDAX) and scanning electron microscopy studies revealed different results from X-ray diffraction (XRD). For the synthesis of ZnO, the leaves of *Azadirachta indica* of Meliaceae family have been of utmost used (Bhuyan et al. 2015). Flower and leaf of *Vitex negundo* plant attributed similar size nanoparticles of 38.17 nm by the Debye–Scherrer equation of XRD (Ambika and Sundrarajan 2015). A functional group such as alcohol, alkane, carbonate, amide, carboxylic acid, and amine is confirmed by FTIR studies in the involvement of nanoparticle synthesis.

Some ZnO nanoflowers were synthesized by *B. licheniformis* which were uniform in size and revealed highly enhanced photostability and photocatalytic activity for methylene blue (MB) dye degradation. These nanoflowers degrade 83% dye, while self-degradation of methylene

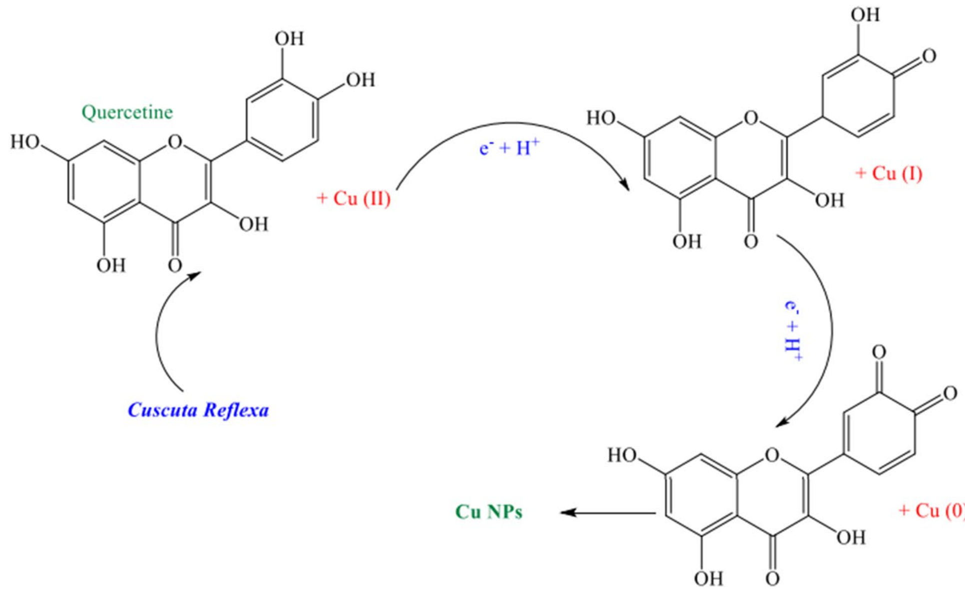

Fig. 11 Biosynthesis of Cu nanoparticles by using *Cuscuta reflexa* leaf extract. Reprinted from Naghdi et al. (2018) with permission from Elsevier

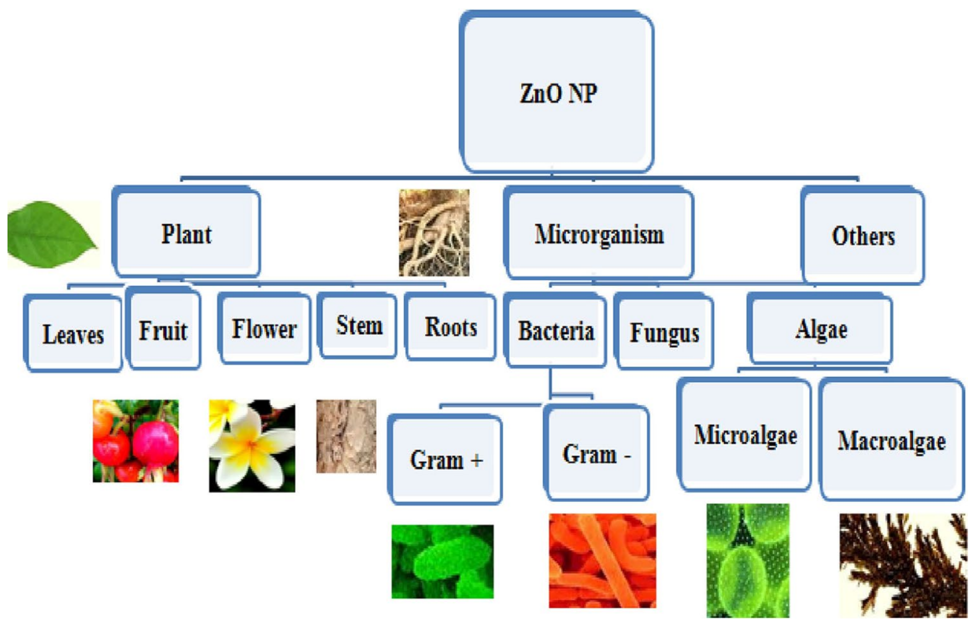

Fig. 12 Biosynthesis of zinc oxide (ZnO) nanoparticles using plants, microorganisms, and others. Reprinted from Agarwal et al. (2017) with permission from Elsevier

blue was null, and at a different time interval, three repeated cycles of the experiment showed 74% degradation which undoubtedly exhibited photostability of ZnO nanoflowers formed (Auld 2001). *Lactobacillus plantarum* was used in the synthesis of ZnO nanoparticles, which were found moderately stable with zeta potential value of − 15.3 mV (Selvarajan and Mohanasrinivasan 2013).

TiO_2 nanoparticles

Titanium oxide nanoparticles are of great interest as these exhibit exclusive morphologies and surface chemistry. These nanoparticles are very useful in the preparation of textiles, plastics, papers, tints, cosmetics, foodstuffs, etc. TiO_2 nanoparticles in the colloid form are vigorously used in the reduction of various toxic chemicals such as pollutants and dyes from water. Green synthesis of TiO_2 nanoparticles from plants is a better choice for toxic-free synthesis. Up to now, numerous plants have been used for its synthesis and applications. The synthesis starts with the reaction of a plant extract with TiO_2 salt. Initially, preparation of nanoparticle can be confirmed by the change in color of the reaction mixture, after that the morphological and spectroscopic studies confimed their formation. These nanoparticles are reported in light green to dark green color. TiO_2 nanoparticles in spherical shape were synthesized by the reaction of leaf extract of *Annona squamosa L* and an aqueous solution of TiO_2 salt at room temperature (Roopan et al. 2012). The reason for choosing mainly leaf extracts to synthesize TiO_2 nanoparticles is leaf extracts are always a rich source of metabolites. TiO_2 nanoparticles were synthesized by Goutam et al. (2018) by leaf extract of *Jatropha curcas* which was confirmed by ultraviolet–visible, Fourier transform infrared spectroscopy (FTIR), X-ray diffraction, scanning electron microscopy, energy-dispersive spectroscopy, dynamic light scattering, and Brunauer–Emmett–Teller analysis, Fig. 13.

Likewise, *Catharanthus roseus* leaf extract was used to synthesize 25–110 nm TiO_2 nanoparticles with irregular morphologies. In the leaf extract, the presence of aliphatic amines and alcohols was responsible for nanoparticle synthesis (Velayutham et al. 2012). Irregular shaped and size of 100-nm TiO_2 nanoparticles were synthesized by *Moringa oleifera* leaf extract having superior wound healing capability (Sivaranjani and Philominathan 2016). Similarly, nanoparticles were achieved in 6 h by using *Calotropis gigantea* leaf extract. Primary amines in the extract were responsible for high bioreduction. These nanoparticles revealed outstanding acaricidal activity against the larvae of *Haemaphysalis bispinosa* and *Rhipicephalus microplus* (Marimuthu et al. 2013). The uniform spherical size nanoparticles were fabricated by using *Cucurbita pepo* seeds extract (Abisharani et al. 2019). Recently, synthesized nanoparticles from plants, their properties, and applications are mentioned in Table 1.

Applications

At present, there is an increasing demand for nanoparticles commercially due to their broad area of applications in industries (Stark et al. 2015), biomedical fields (Subbiah et al. 2010), electronics (Balantrapu and Goia 2009), markets (Bergmann and de Andrade 2011), energy (Frey et al. 2009), and especially in chemistry (Louis and Pluchery 2012). Nanoparticles are of great interest for biomedical applications such as silver and gold nanoparticles that are most common which have been used in this field as well as the emerging interdisciplinary field of nanotechnology, Fig. 14.

Gold nanoparticles have also been used specifically in cancer therapy for the detection of cancer cells, protein assay, immunoassay, and capillary electrophoresis. In the medicine field, gold nanoparticles have of great interest. For biological screening tests, they can be used as biomarkers. To kill cancers, these treat as accurate and influential heaters after cellular uptake. Along with these, they can induce apoptosis in B cell-chronic lymphocytic leukemia. Significant antioxidant capacity was revealed by gold nanoparticles produced by the leaf of *Suaeda monoica*, and DPPH radical-scavenging activity of these was found 43% at 1 mg/ml (Arockiya Aarthi Rajathi et al. 2014). Good antioxidant activity was also shown by using leaf extract of *Nerium oleander* on the various concentration of gold nanoparticles. On increasing concentration of nanoparticles, antioxidant activity was found to increase (Tahir et al. 2015). Gold nanoparticles extracted by *Gymnocladus assamicus* exhibited the great catalytic activity in reduction to 4-aminophenol from 4-nitrophenol (Tamuly et al. 2013). Outstanding catalytic performance was shown in the reduction of methylene blue dye by gold nanoparticles extracted from *Sesbania grandiflora* plant. Results for these showed decrement of methylene

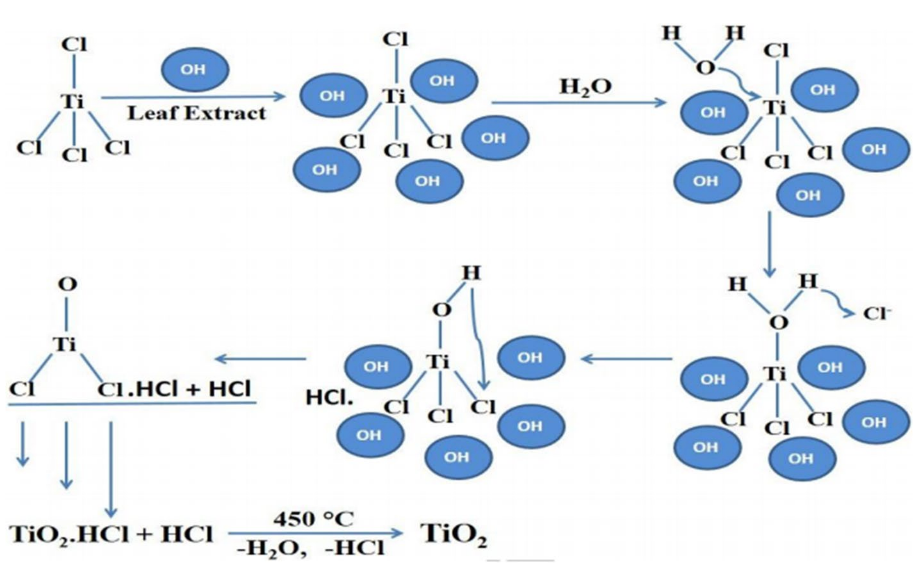

Fig. 13 Possible mechanism for synthesis of TiO_2 nanoparticles by hydroxyl group of *Jatropha curcas* leaf extract. Reprinted from Goutam et al. (2018) with permission from Elsevier

Table 1 Synthesized biogenic nanoparticles using plant extracts

Year	Nanoparticle	Plant origin	Size (nm)	Morphology	Application	References
2020	Au	*Gelidium pusillum*	12 ± 4.2	Spherical	Anticancer activity	Jeyarani et al. (2020)
2020	Au	*Hibiscus sabdariffa*	15–45	Spherical	Antiacute myeloid leukemia	Zangeneh and Zangeneh (2020)
2020	Au	*Pimenta dioica*	13 ± 4	Spherical	Anticancer activity	Kharey et al. (2020)
2020	Au	*Croton sparsiflorus*	16.6–17	Spherical	UV-protection, antibacterial, and anticancer agents.	Boomi et al. (2020)
2020	Au	*Desmodium gangeticum*	16 ± 4	Spherical	Antioxidant	Ghosh et al. (2020)
2020	Au	*Litsea cubeba*	8–18	Spherical	Catalytic reduction of 4-nitrophenol	Doan et al. (2020)
2020	Ag	*Dionaea muscipula*	5–10	Quasi-spherical	Antioxidant	Banasiuk et al. (2020)
2020	Ag	*Elaeagnus umbellata*	40	Spherical	Antimicrobial	Ali et al. (2020)
2020	Ag	*Reishi Mushroom*	15–22	Spherical	Antifungal	Aygün et al. (2020)
2020	Ag	*Cestrum nocturnum*	20	Spherical	Antioxidant and antibacterial	Keshari et al. (2020)
2020	Ag	*Malus domestica*	16	–	Antimicrobial	Kazlagić et al. (2020)
2020	Ag	*Nauclea latifolia*	12	Irregular	Antimicrobial and antioxidant	Odeniyi et al. (2020)
2020	Cu	*Orobanche aegyptiaca*	< 50	Spherical	Nematicidal activity	Akhter et al. (2020)
2020	Cu	Walnut shells	15–22	–	Antibacterial, antioxidant, and anticancer	Mehdizadeh et al. (2020)
2020	Cu	*Anacardium occidentale*	< 20	Irregular spherical	Efficient removal of uranium	Chandra and Khan (2020)
2020	Cu	*Hagenia abyssinica*	34.76	Spherical, hexagonal, triangular, cylindrical	Antimicrobial	Murthy et al. (2020)
2020	Pd	*Cotton boll peels*	9.44	Spherical	Catalytic activity against toxic azo-dyes	Narasaiah and Mandal (2020)
2020	Pd	*Syzygium aqueum*	5–20	Irregular	Catalysis in the coupling reaction	Manjare and Chaudhari (2020)
2020	Pd	*Rosmarinus officinalis*	15–90	Semi-spherical	Mizoroki–Heck catalytic, antibacterial, and antifungal activities	Rabiee et al. (2020)
2020	Pt	*Nigella sativa L.*	1–6	Spherical	Antimicrobial and anticancer agent	Aygun et al. (2020)
2020	Pt	*Prosopis farcta fruits*	3.5	Irregular	–	Jameel et al. (2020)
2020	Pt	*Phoenix dactylifera L.*	2.3–3	Spherical	Toxic and protective effects on CCl_4-induced hepatotoxicity in Wister rats	Al-Radadi and Adam (2020)
2020	Pt	*Tragia involucrata*	10	Spherical	Biomedical & pharmaceutical applications	Selvi et al. (2020)
2020	ZnO	*Prosopis juliflora*	31.80–32.39	Irregular	Degradation of methylene blue dye	Sheik Mydeen et al. (2020)
2020	ZnO	*Acalypha fruticosa*	50	Spherical, hexagonal	Antimicrobial	Vijayakumar et al. (2020)
2020	ZnO	*Calotropis gigantea*	31	Hexagonal and pyramidal	Nitrite sensing, photocatalytic, and antibacterial	Kumar et al. (2020)
2020	ZnO	*Urtica dioica*	20–22	Spherical	Antidiabetic	Bayrami et al. (2020)
2020	TiO_2	Lemon peel extract	80–140	Spherical	Photocatalytic activity	Nabi et al. (2020)
2020	TiO_2	*Mentha arvensis*	20–70	Spherical	Antimicrobial	Ahmad et al. (2020)

Table 1 (continued)

Year	Nanoparticle	Plant origin	Size (nm)	Morphology	Application	References
2020	TiO_2	Alcea and Thyme extract	10	Polyhedron and irregular	Photocatalytic activity	Arabi et al. (2020)
2020	TiO_2	*Syzygium cumini*	11	Spherical	Photocatalytic removal of lead	Sethy et al. (2020)
2020	TiO_2	*Ledebouria revoluta*	47	Tetragonal	Histopathological, larvicidal, antibacterial, and anticancer activity	Aswini et al. (2020)

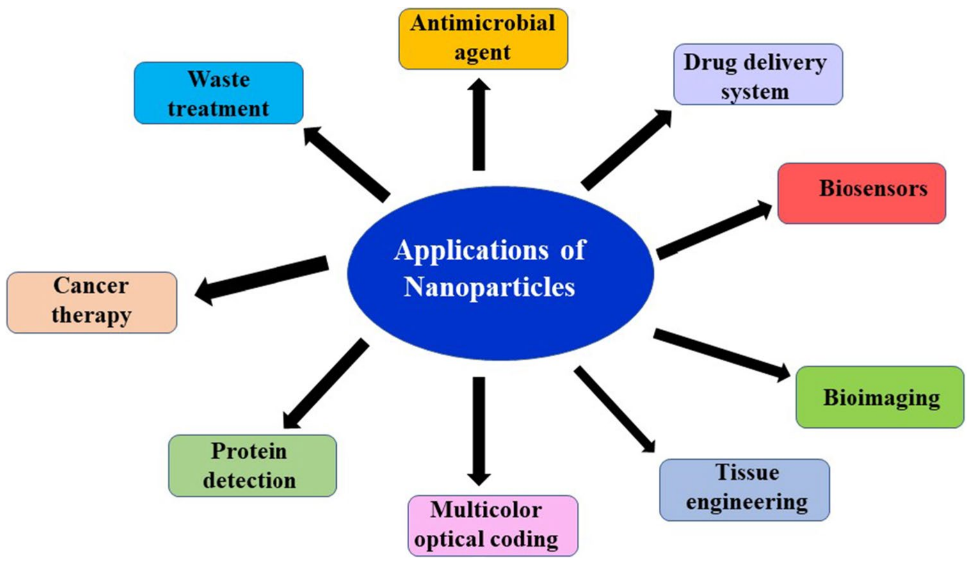

Fig. 14 Applications of green synthesized nanoparticles in environmental and biomedical fields

blue absorbance value with time (Das and Velusamy 2014). The same dye was reduced by photocatalytic activity of Au nanoparticles extracted by the leaf of *Pogestemon benghalensis*. These nanoparticles were free from agglomeration, synthesized without any external reducing agent (Paul et al. 2015). Congo red and reactive yellow 179 dyes were decolored by photocatalytic activity using gold nanoparticles synthesized by using *Eucommia ulmoides* (Guo et al. 2015).

Silver nanoparticles have drawn considerable attention from researchers and scientists due to their wide area of applications like biolabeling, sensors, antimicrobial activity, antibacterial activity, cell electrodes, integrated circuits, etc. Due to showing antimicrobial activity, these are applicable in numerous fields such as medicine, health, packaging, animal husbandry, various industries, military, cosmetics, and accessories. Against infectious organisms such as *Staphylococcus Aureu, Vibria cholera*, *Bacillus subtilis*, *Syphillis typhus*, *Pseudomonas aeruginosa*, and *Escherichia coli*, these nanoparticles showed potential antimicrobial effects.

The green synthesized TiO_2 nanoparticles have a broad area of applications such as tissue engineering, sensing, imaging, disease diagnostics, manufacturing of surgical tools, treatment, agriculture, and energy production, etc. TiO_2 nanoparticles derived by *Hibiscus rosa sinensis* exhibited excellent antimicrobial activity against both Gram-positive and Gram-negative strains of bacteria (Kumar et al. 2014). Similarly, TiO_2 nanoparticles are widely applicable in the degradation of various pollutants such as nitroarene compounds and toxic dyes. Their large surface area, recyclability is a key feature to make it a heterogeneous catalyst. The reduction of dyes and pollutants by TiO_2 nanoparticles have been reported by various authors. Figure 15 represents the photocatalytic mechanism and electron flow by photoexcitation which results in the degradation of various dyes and pollutants. TiO_2 nanoparticles synthesized by green route were also applied to testify for removal of chromium (Cr) and chemical oxygen demand (COD) from secondary treated tannery wastewater. About 76.48% removal of Cr and 82.86% removal of COD from tannery wastewater (TWW) were attained on Parabolic Trough Reactor with the treatment using green synthesized TiO2 nanoparticles (Goutam et al. 2018).

Nanoparticles of palladium and platinum are widely used in many medical diagnoses without destructing the deoxyribose nucleic acid (DNA) structure, Fig. 16 (Thakkar et al. 2010). Some Pd nanoparticles were useful in photocatalytic

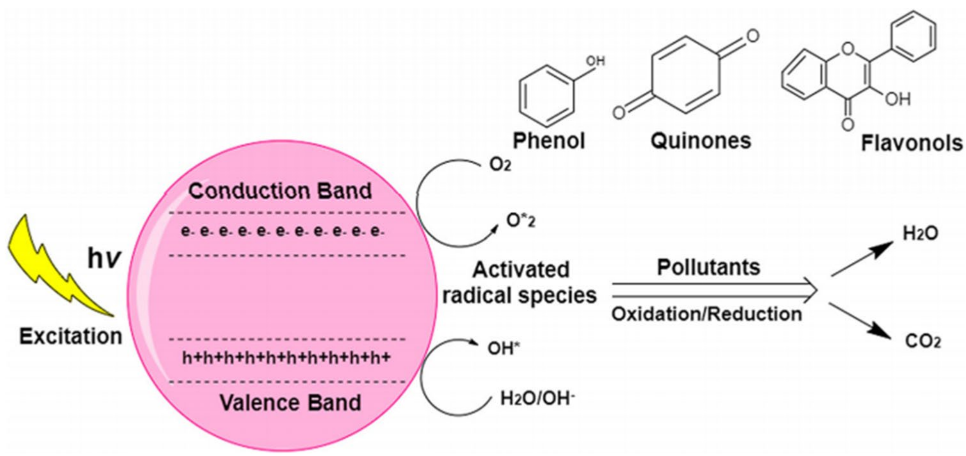

Fig. 15 Photocatalytic mechanism of TiO_2 nanoparticles and electron flow by photoexcitation under light source resulting in degradation of various dyes and pollutants. Reprinted from Nadeem et al. (2018) with permission from Taylor & Francis

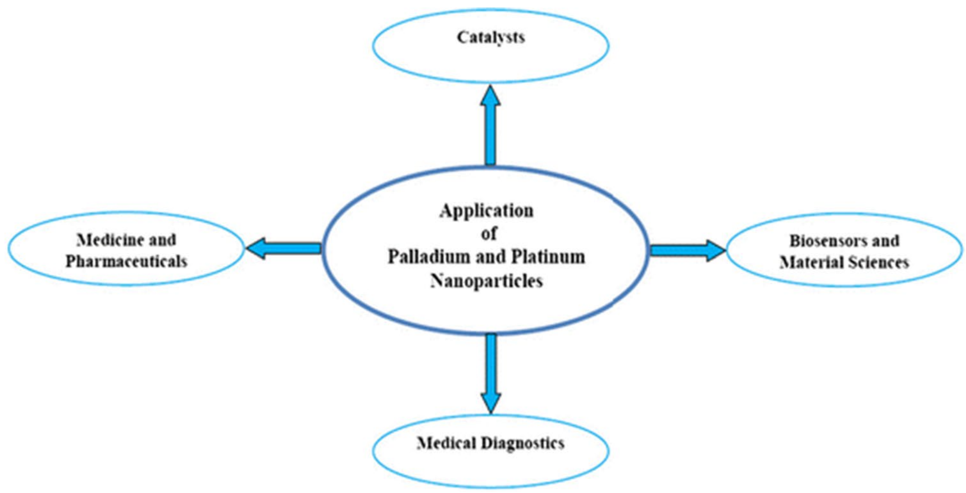

Fig. 16 Applications of palladium and platinum nanoparticles in chemistry, biology, and material science fields. Reprinted from Siddiqi and Husen (2016) with permission from Springer

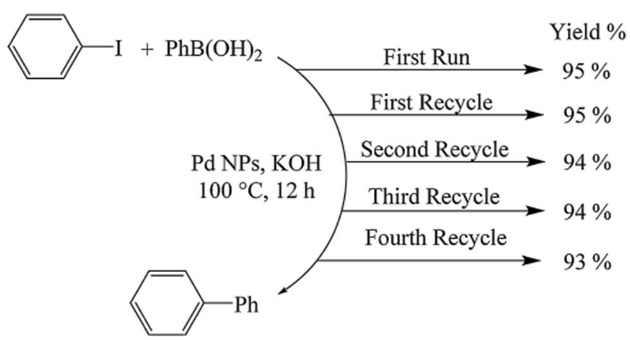

Fig. 17 Reusability of Pd nanoparticles in Suzuki–Miyaura coupling reaction and the percentage of yield of the catalyst after every run. Reprinted from (Nasrollahzadeh et al. 2015b) with permission from Elsevier)

activity for phenol red dye degradation at pH 6. The dye degradation studies were performed on various pH ranging from 2 to 10 of various aliquots of palladium nanoparticle solutions. The surface plasmon resonance (SPR) spectroscopy revealed the disappearance of 433 nm band at pH 6 and concluded the optimum pH range for phenol red dye degradation by Pd nanoparticles (Kalaiselvi et al. 2015).

Palladium nanoparticles were derived by *Hippophae rhamnoides Linn* leaf extract have been studied in Suzuki–Miyaura coupling reaction for heterogeneous catalytic activity. In the Suzuki–Miyaura coupling reaction, Pd nanoparticles work as a catalyst. The recycling of catalyst decreases the process cost, and it was easily separated from the reaction mixture by centrifugation after completion of the reaction. The recovered catalyst was efficaciously used without noteworthy activity loss for four fresh runs, Fig. 17. The leaching phenomena were studied for heterogenicity of the catalyst by inductively coupled plasma atomic emission spectroscopy analysis. During the reaction, the total amount of 0.2% palladium vanished only (Nasrollahzadeh et al. 2015b).

Some Pd nanoparticles revealed outstanding antioxidant properties at a lesser dose of nanoparticle, as well as these nanoparticles, worked as nanocatalyst for environmental remediation by showing catalytic activity in the reduction of dyes such as methyl orange, methylene blue, coomassie brilliant blue G-250, and reduction of 4-nitrophenol (Kora and Rastogi 2018). Platinum nanoparticles were used for evaluation of anticancer activities using four various cancer cells such as hepatocellular carcinoma (HePG-2), breast cells (MCF-7), and colon carcinoma cells (HCT-116), and promising results were obtained with Ajwa extract. Likewise, Barni extract effects were obtained on hepatocellular carcinoma cells (HepG-2) and also inhibited the cells of breast cancer cells (MCF-7) and colon cancer (HCT) to a noteworthy range. In this study, well-known anticancer agent, doxorubicin HCl, was used for comparative study. These platinum nanoparticles inhibited the growth of Gram-positive bacteria *Bacillis subtilis* (RCMB 010067) and Gram-negative bacteria *Escherichia coli* (RCMB 010052) (Al-Radadi 2019).

Conclusion

During the last some decades, increasing demand for green chemistry and nanotechnology pushes toward the adoption of green synthetic routes for the synthesis of nanomaterials via plants, microorganisms, and others. Green synthesis of nanoparticles has been the area of focused research by researchers in the last years by adopting an eco-friendly approach. Much research has been carried out on the plant extract-mediated nanoparticles synthesis and their potential applications in various fields due to their cost-effectiveness, nontoxic route, easy availability, and environment-friendly nature. Moreover, they have a wide area of applications such as catalysis, medicine, water treatment, dye degradation, textile engineering, bioengineering sciences, sensors, imaging, biotechnology, electronics, optics, and other biomedical fields. Additionally, plants contain some unique compounds which help in synthesis as well as increases the rate of synthesis. The use of plants for green synthesis of nanoparticles is an exciting and developing part of nanotechnology and has a noteworthy effect on the environment toward sustainability and further development in the field of nanoscience. The future expectations from the green route of nanoparticles synthesis are that the applications of these will grow exponentially, but there is a need to concern about the long-term effects of these on animal and human being as well as accumulation of these in the environment is a subject of worry which has to be resolved in future. These biogenic nanoparticles can be used in nanoweapons against phytopathogens as well as in the disinfection of water in various forms for environmental remediation. In the drug delivery system, these nanoparticles might be the future thrust for the biomedical field.

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Compliance with ethical standards

Conflict of interest There is no conflict of interest.

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